GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L00E19, doi:10.1029/2010GL042558, 2010

Insights into processes and deposits of hazardous vulcanian explosions at Soufrière Hills Volcano during 2008 and 2009 (Montserrat, West Indies)

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Received 19 January 2010; revised 9 March 2010; accepted 15 March 2010; published 5 June 2010.

[1] During the Soufrière Hills eruption, vulcanian explosions have generally occurred 1) in episodic cycles; 2) isolated during pauses in extrusion, and 3) after major collapses of the dome. In a different eruptive context, significant vulcanian explosions occurred on 29 July 2008, 3 December 2008, and 3 January 2009. Deposits are pumiceous except for the 3 December event. We reconstructed the dispersal pattern of the deposits and their textural characteristics to evaluate erupted volume and vesicularity of the magma at fragmentation. We discuss the implications of these explosions in terms of eruptive processes and chronology, and the hazards posed by their sudden and often unheralded occurrence. We suggest that overpressurization of the conduit can develop over time-scales of months to weeks by a process of self-sealing of conduit walls and/or the cooling dome by silica polymorphs. This work provides new insights for understanding the generation of hazardous vulcanian explosions at andesitic volcanoes.

Citation: Komorowski, J.-C., et al. (2010), Insights into processes and deposits of hazardous vulcanian explosions at Soufrière Hills Volcano during 2008 and 2009 (Montserrat, West Indies), *Geophys. Res. Lett.*, *37*, L00E19, doi:10.1029/2010GL042558.

1. Introduction

[2] Since it's beginning in July 1995, the eruption of Soufrière Hills Volcano (SHV) has produced nearly 1 km^3 of andesitic magma in fourteen years, during five phases of extrusive growth separated by non-extrusive pauses of varying duration [*Wadge et al.*, 2010; Montserrat Volcano Observatory, Weekly activity reports and open file report archive, 1995–2010, http://www.mvo.ms]. The eruptive activity has been dominated by countless rockfalls and block-and-ash flows from gravitational instability of the growing dome. This pattern has been interrupted on numerous occasions by short-lived vulcanian explosions of varying magnitude. A synthesis of the chronology of Phase 4 (29 July 2008–3 January 2009) of the eruption can be found in Text S1 of the auxiliary material.[9] All dates are based on UTC time (Eastern Caribbean Standard time + 4 hours).

[3] Vulcanian explosions at SHV have occurred in three main eruptive contexts: 1) two episodes of cyclic explosions in 1997 with 13 events between 4 and 12 August, and 75 events between 22 September and 21 October [*Druitt et al.*, 2002; *Bonadonna et al.*, 2002]; 2) isolated throughout a period of little or no extrusion such as between March 1998 and November 1999 [*Norton et al.*, 2002]; and 3) simultaneously or shortly after most major collapses of the lava dome such as on 20 March 2000, 13–15 July 2003, 20 May 2006, and 8 January 2007, and 11 February 2010 [*Herd et al.*, 2005; *Edmonds et al.*, 2006; *Loughlin et al.*, 2007; Montserrat Volcano Observatory, Weekly activity reports and open file report archive, 1995–2010, http://www.mvo.ms]. Vulcanian explosions have ejected ballistic blocks up to a distance of about 3 kilometers, produced fallout of dense to vesicular tephra up to 10 km from source from non-sustained short-lived eruption columns that reached up to 15 km in height before producing fountain-collapse pyroclastic flows and surges.

[4] In a different eruptive context, two types of vulcanian explosions occurred during Phase 4 of the eruption. On 29 July 2008 and 3 January 2009 they produced pumiceous fallout and flow deposits. However, on 3 December 2008 an explosion produced non-pumiceous surge and block-and-ash flow deposits. Here we provide a description of the field and textural characteristics of their ephemeral deposits. We discuss the implications of these two types of explosions in terms of eruptive processes, the chronology of the eruption, and the hazards posed by their occurrence with little or no obvious precursory activity.

2. Eruption Products

2.1. The 29 July 2008 Pumice Fallout

[5] An explosion on 29 July 2008 scattered coarse vesicular pumice lapilli and coarse dense accidental lapilli on the ground without forming a continuous deposit (Figure S1). They were dispersed NW of the volcano throughout a partly

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0094-8276/10/2010GL042558

[9]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042558.

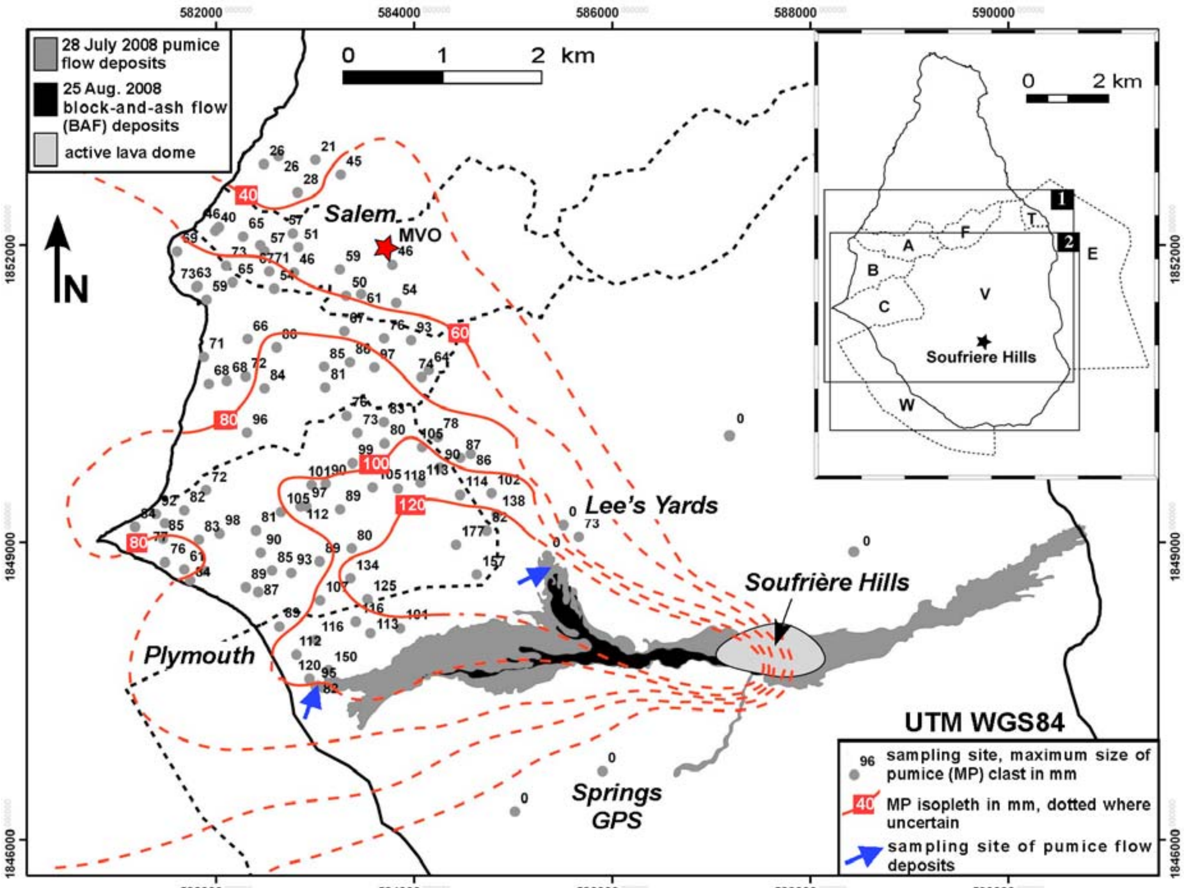

Figure 1. Map of maximum pumice (MP) isopleths (mm) for fallout deposit and of pumice pyroclastic flow deposits from the 29 July 2008 vulcanian explosion. The 25 August 2008 block-and-ash flow deposit is also shown. Insert: Hazard Level System (HLS) zones implemented on Montserrat (Government of Montserrat, see http://www.mvo.ms).

populated area along an azimuth of 310° (Figure 1). The major axis of the five largest juvenile pumice clasts (MP) and the five largest accidental clasts (ML) was measured at 106 localities. Contour lines with the same average maximum pumice (MP) size in mm (isopleths) were then interpolated from existing data (Figure 1). The mean uncertainty (one standard deviation) on the MP size for all 106 sites is 11 mm (13%). Isopleths show that the 29 July 2008 pumice fallout was very coarse. Maximum pumice sizes reach 21–97 mm 5–7 km from the vent in populated areas (ML = 12–54 mm) (Figure 1). This is significantly coarser than the subplinian fallout deposit described by *Robertson et al.* [1998] and fallout from vulcanian eruptions in 1997 [*Bonadonna et al.*, 2002; *Druitt et al.*, 2002]. The lobate dispersal pattern suggests that pumice fallout was influenced by different wind regimes at different elevations (Figure S4), that pumice ejection might have been unsteady as suggested by the complex seismic and infrasonic signals [*Ripepe et al.*, 2009; 2010; *Stewart et al.*, 2008] or that it might have involved some directed component from the vent.

2.2. The 3 January 2009 Pumice Fallout

[6] A series of 4 explosions of increasing intensity occured overnight on 3 January 2009 within a period of 4 hours at 6:55, 8:13, 8:46, and 11:06 UTC with the last being the most intense. Fresh vesicular pumice coarse lapilli and dense accidental coarse lapilli were scattered extensively over most of Southern Montserrat. A continuous sheet of pumice 1 to 8 cm thick accumulated within 4 km SW of the volcano with a dispersal axis 250° from north. (Figure S1). There was no impact on inhabited areas. Isopachs for the cumulative pumice fallout deposit that resulted from the 11:06 event and perhaps also the 8:46 event are shown in Figure 2. We use the same method as for the 29 July deposits to reconstruct isopleths of the maximum pumice (MP) size in mm for 3 January 2009 (white circles, Figure 2) based on measurements at 31 localities. The mean uncertainty (standard deviation) on the MP size for all 31 sites is 10 mm (11%). The pumice and lithic clasts were coarser and distributed over a much wider area than those of 29 July 2008.

[7] The deposit forms a loose, reversely graded, poorly to very poorly-sorted (Inman Sorting coefficient $\sigma\Phi = 1$ to 1.7), clast-supported and fines-poor, massive coarse to very coarse lapilli pumice sheet (Inman median diameter $Md\Phi = -4.7$ or 26 mm; the 16–32 mm size fraction represents up to 43 wt. % of the total sample). It rests locally on a massive 5–15 cm-thick compact fine gray ash deposit that overlyies dried and singed grass (Figure S1). This unit represents a cumulative ashfall deposit for the intense period of activity that developed from 3 December 2008 to 3 January 2009 including material from the widespread 3 December 2008

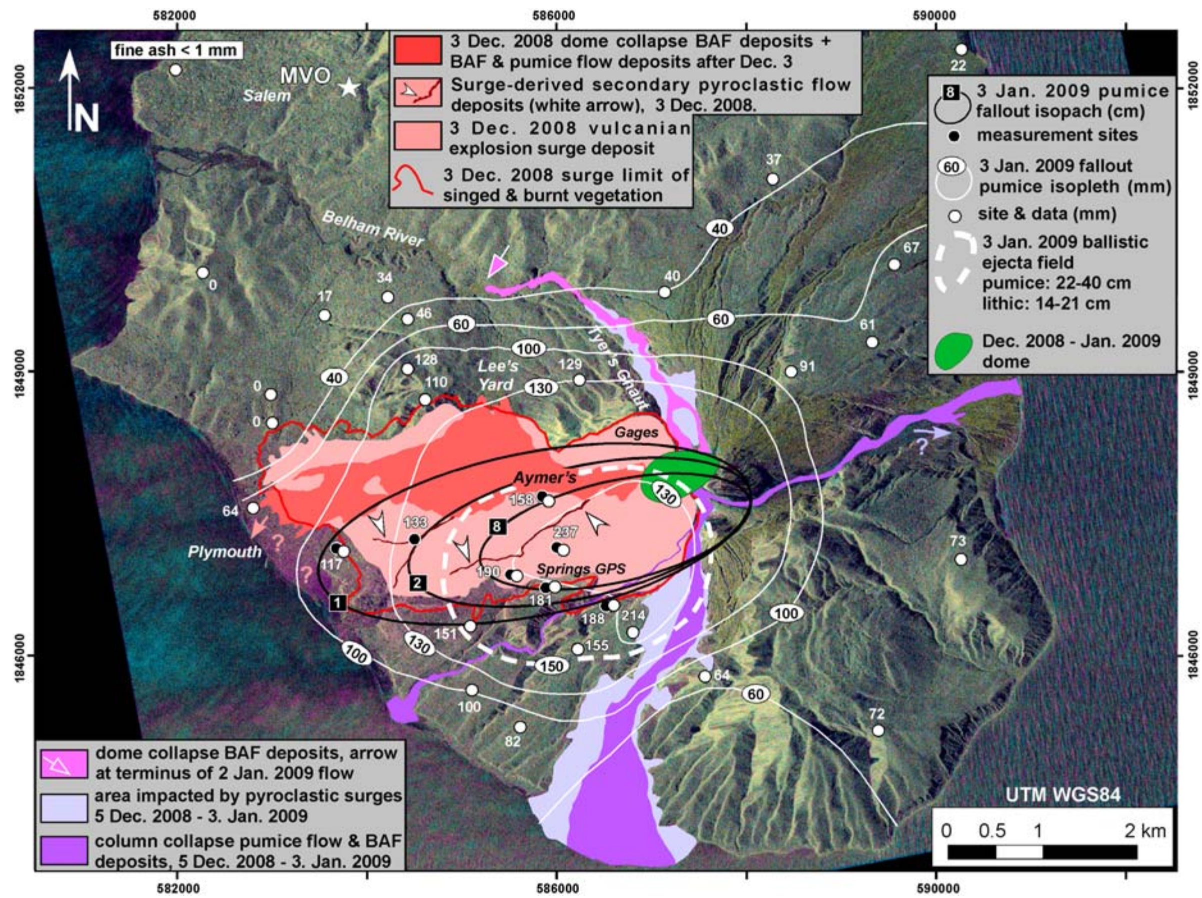

Figure 2. Map of deposits produced during the 3 December 2008 to 3 January 2009 eruptive phase including vulcanian explosions on 3 December and 3 January (see map insert for legend, BAF: block-and-ash-flow). TerraSAR-X background difference image for the period 11 December 2008–2 January 2009, courtesy DLR, Germany.

pyroclastic surge. Large blocks of pumice and dense dome-rock (20 to 40 cm in diameter) were ballistically ejected up to a maximum distance of 2.8 km to the S and SW during the vulcanian explosions on 3 January 2009 (Figure 2).

2.3. Pumice Pyoclastic Flows

[8] The extent of pumiceous flows and block-and-ash flows from eruptive activity from 29 July 2008 through 3 January 2009 is shown on Figures 1 and 2. Pyroclastic flow deposits from fountain collapse form a network of anastomosing narrow and sinuous pumice-rich lobes. They have highly digitated flow fronts and well-developed, fines-poor, clast-supported levees with larger pumice clasts ≤1 m in diameter. Individual flow deposits from 29 July 2008 are 1 to 1.5 m thick in the central part. The deposits are composed largely of subrounded to rounded pumice clasts (≤20 cm in diameter; 70 wt% pumice in 8–16 mm size fraction) set in a matrix of coarse to fine pinkish tan ash. These deposits are analogous to deposits from the 1997 vulcanian explosions that were described in detail by *Cole et al.* [2002] and *Druitt et al.* [2002]. At Lee's Yard and in Plymouth, the 29 July 2008 (Figure 1) pumice-flow deposits are underlain by a well-developed, wavy-bedded, well-sorted and fines-rich, sandy, 1–3 cm thick co-erupted pyroclastic surge unit.

2.4. The 3 December 2008 Explosion and Dome Collapse Products

[9] Unfortunately deposits from the 3 December vulcanian explosion and partial dome collapse could not be sampled in the field due to safety issues. Subsequent fieldwork (Figures 2 and S2) revealed that most of these deposits had been eroded. All observations by the MVO [*Stewart et al.*, 2009] indicate that they lacked pumiceous material but consist of dense clasts from the former dome that had remained hot and pressurized (Figure S5). This is consistent with the fact that borehole strainmeters data for this explosion cannot be modelled satisfactorily with a 2 km long pressurized conduit filled with non-degassed magma as for the 29 July and 3 January explosions (L. Chardot et al., Explosion dynamics from strainmeter observations, Soufrière Hills Volcano, Montserrat, W.I.: 2008–2009, manuscript in preparation, 2010). We estimate a DRE volume of 1.36 Mm^3 with a volume of 1.17 Mm^3 for pyroclastic flow and 0.15 to 0.19 Mm^3 for pyroclastic surge deposits.

2.5. Lithology of Pumiceous Vulcanian Products

[10] The fallout consists of variably vesicular whitish to grey juvenile pumice (65 wt. %), rich in large crystals of plagioclase and hornblende (up to 1–2 mm) (Figures S1 and S4). The conspicuous platy tabular shape of many vulcanian

pumice clasts indicates an origin from brittle fragmentation of an already over-pressured vesicular magmatic foam [*Druitt et al.*, 2002; *Edmonds et al.*, 2006]. The fallout deposit also contains numerous angular accidental clasts (34 wt. %) of vitric dome rock and a few hydrothermally altered accidental clasts. Pumice clast vesicularity measured on the dominant 16–32 mm size fraction differs for the 2008 and 2009 events (see Figure S3). Scattered pumice clasts from the 29 July 2008 explosion have a mean density of 960 ± 210 $kg.m^{-3}$ and a mean vesicularity of 63 ± 8% (powder DRE density of 2640–2680 $kg.m^{-3}$). In contrast, pumice clasts from the 3 January 2009 continuous fallout deposit sampled at two sites have a mean density of 1080 ± 210 and of 1180 ± 240 $kg.m^{-3}$ (mean vesicularity of 59 ± 7% and 56 ± 9% respectively). Pumice clasts from the 3 January 2009 explosion fallout are thus less vesicular and show a clear bimodal distribution (dominant mode 1 at 950 $kg.m^{-3}$ and a subordinate mode 2 at 1350 $kg.m^{-3}$) compared to pumice clasts from the 29 July 2008 explosion fallout. Vulcanian pumiceous deposits in 2008 and 2009 contain conspicuous mafic enclaves that can be readily recognized in the field at all scales (for 301 clasts 32–64 mm in size randomly collected at three different sites for the 29 July pumice, 12.3% were an enclave or contained a large mafic enclave).

3. Discussion and Conclusions

[11] The activity that developed at SHV between 29 July 2008 and 3 January 2009 (Phase 4, see Text S1) differs from other eruptive phases of the ongoing eruption inasmuch as it began and ended with vulcanian pumice-bearing explosions with no immediate precursory activity. Extrusive activity occurred in two short bursts (phase 4A from 29 July to 1 October 2008, and phase 4B from 3 December 2008 to 3 January 2009). Moreover, on 3 December 2008 a non-pumiceous vulcanian explosion marked the onset of phase 4B. Understanding the causes of pressurization of the magmatic conduit and/or the dome, as well as the trigger for vulcanian explosions is essential for improving explosion forecasting and risk assessment.

[12] The powerful vulcanian explosions on 29 July 2008 and 3 January 2009 evacuated the conduit filled with a partly to non-degassed pressurized magma column and produced relatively high eruption columns (10–12 km) as well as moderately to well-vesiculated pumice fallout. Modelled drawdown depths of 0.34 to 3.3 km [*Voight et al.*, 2009; Chardot et al., manuscript in preparation, 2010] are comparable to previous vulcanian explosions in 1997 [*Druitt et al.*, 2002; *Clarke et al.*, 2002].

[13] Although the 29 July 2008 and 3 January 2009 explosions bear similarities, marked differences between the two events are likely linked to the eruptive context in which bubbly magma ascended in the conduit prior to the explosion. Both explosions produced similar DRE volumes of magma of about 1.36×10^6 (29 July) and about 1.16×10^6 m^3 (3 January). These volumes are almost one order of magnitude greater than the average total DRE volume (3×10^5 m^3) of magma discharged during each vulcanian explosion in 1997 [*Druitt et al.*, 2002]. The eruption column was higher on 29 July 2008 (12.2 km) and all the volume was erupted in one powerful explosion in contrast to at least two tephra-producing explosions on 3 January 2009 (10.6 km column). Pumice from 29 July 2008 is noticeably more vesicular than pumice from 3 January 2009. This suggests that volatile gradients in the magma were more pronounced for the January event. Moreover, it suggests that January 2009 magma had lost more volatiles during its ascent or contained initially less volatiles than July 2008 magma. The mass eruption rate was likely higher for the July event than for the January explosions. Mass in the July 2008 explosion was dominantly partitioned into the collapsing rather than buoyant convective part of the column. Very different wind regimes (Figure S4) strongly controlled the dispersal pattern of pumiceous tephra during the 29 July and 3 January eruptions and the impacted zones on island.

[14] The 29 July 2008 explosion occurred after a 13-month pause in extrusive activity and was preceded by several small explosions and ash venting events [*Stewart et al.*, 2008]. Scanning electron microscope (SEM) analysis shows that fine-grained ash on 5 and 13 May 2008 contained 5–10% of white unaltered highly microvesicular pumice grains rich in green hornblende crystals (Figure S5a). These pristine fragments represent juvenile magmatic precursors of the 29 July vulcanian pumice and indicate that gas-rich magma was present at that time in the deeper conduit below the large dome.

[15] Tephra erupted in May 2008 also contained 10–20% hydrothermally altered fragments displaying conduit margin microtextures and abundant hydrothermal and vapor-phase silica with vein-filling pyrite [*Komorowski et al.*, 2008; *Stewart et al.*, 2008]. Hence the permeability of the conduit–country rock interface and the dome was reduced by silicification [*Komorowski et al.*, 1997]. The resulting partial seal prevented significant pre-eruption degassing of the bubbly magma erupted on 29 July (Figure S5).

[16] The long-term mean SO_2 emission rate (LTM) for the entire eruption (1995–2009) is 570 tons per day [*Christopher et al.*, 2010]. This represents the continuous exsolution of sulfur-rich gases from mafic magma at depth and their migration to the shallow andesitic volcanic system [*Edmonds et al.*, 2003a; *Christopher et al.*, 2010]. By advecting heat to the andesitic magma, increasing its bulk volatile concentration, and affecting it's buoyancy, continued injection of mafic magma at depth drives the eruption of andesite magma at the surface [*Christopher et al.*, 2010]. In a marked departure from established long-term trends, the SO_2 emission rate remained well below the LTM with a mean of 302 ± 102 tons/day between 30 May and 15 July (see Figure S6) [*Stewart et al.*, 2008; *Robertson et al.*, 2009]. During the same period, GPS data seemed to suggest continued inflation of the shallow-depth andesite magma chamber consistent with mafic injection at depth [*Elsworth et al.*, 2008; *Stewart et al.*, 2008]. Thus, the significant deficit in SO_2 emissions (about 50%) following 47 days of below LTM emissions implies that a significant amount of SO_2 was stored in the volcanic conduit at shallow depth as a result of the reduction of conduit permeabilities by hydrothermal and vapor-phase self-silicification [*Komorowski et al.*, 1997; *Edmonds et al.*, 2003b].

[17] Ascent of a volatile-rich andesite magma initially in a closed-conduit system below the large crystallizing and degassed andesite dome that acted as an effective plug, generated significant overpressure at shallow depth in the conduit (Figure S6). Indeed, 29 July pumice is highly vesicular with extremely thin bubblewalls (0.3 micrometers)

(Figure S5). However in contrast to 1997 vulcanian pumice [*Rutherford and Devine*, 2003], the prominent ca. 100 micrometer-thick breakdown rims on the hornblende phenocrysts, the abundant tabular plagioclase microlites, and occasional vapor-phase cristobalite of 29 July pumice [*Komorowski et al.*, 2008] suggest that the magma experienced closed-system partial degassing as it stagnated in the conduit below the plug. This is consistent with rock-fracturing seismicity (VT) increasing in April, May, and particularly between 21–26 July [*Stewart et al.*, 2008]. As new pathways were opened in the pressurized conduit walls and in parts of the dome (evidenced by recurrent ash venting episodes from 13 May to 26 July) trapped volatiles were partly released starting on 15 July but insufficiently to offset the large deficit in SO_2 emissions.

[18] The remarkably intense hybrid and long-period seismic swarm on 26–27 July [*Stewart et al.*, 2008] (see Text S1) suggests that significant overpressures still existed in the partially sealed upper conduit and plug. This culminated in the 29 July vulcanian explosion which evacuated the foamy magma through a vent on the western side of the dome. It produced a 12-km high ash and pumice-bearing column and a large release of SO_2 gas (≥2000–3000 tons) detected by the OMI spaceborne sensor [*Stewart et al.*, 2008]. Viscous and slow extrusive growth developed shortly in early August 2008. Most of the stiffened magma did not erupt at that time but stagnated, cooling and degassing at shallow depth to form an effective plug. Persistent incandescence through October and November 2008 from fractures on the dome indicated the presence of hot rock at shallow depth [*Stewart et al.*, 2008].

[19] The eruptive context was different prior to the explosive events of the period from 3 December 2008 to 3 January 2009. Continued inflation of the magma chamber in the preceding months [*Robertson et al.*, 2009] indicates that magma was likely ascending towards the surface below the large dome plug. Degassing of SO_2 increased after 29 July 2008 and remained elevated (mean of 900 tons/day) until mid November (Figure S6). This promoted continued rheological stiffening of the magma and ultimately its overpressurization, initially from degassing-induced crystallization [*Sparks*, 1997] and ultimately from partial sealing of pore space with silica polymorphs (Figure S5). A powerful vulcanian explosion ensued on 3 December 2008 that exposed deeper regions of the dome near the Gages vent and generated a widespread pyroclastic surge (Figures 2 and S2) followed by partial dome collapse.

[20] A period of very fast extrusion of partly degassed andesite resumed on 5 December 2008 at a rate that varied but often reached up to 15 $m^3.s^{-1}$ [*Wadge et al.*, 2010]. This favored the rapid ascent of deeper–seated bubbly magma and curtailed volatile loss. The activity escalated on 3 January 2009 with a series of 4 increasingly more intense vulcanian explosions. They evacuated the remainder of the magma column down to depths of up to 3 km [*Voight et al.*, 2009]. Within a few hours of this event, extrusion ceased abruptly marking the start of a pause that lasted until extrusion resumed on 9 October 2009 (Montserrat Volcano Observatory, Weekly activity reports and open file report archive, 1995–2010, http://www.mvo.ms).

[21] It is important to improve our understanding of the processes and timescales that control the pressurization of volcanic conduits and andesitic lava domes as they often lead to unheralded vulcanian explosions and dome instability. The textural analysis of early erupted tephra and of ephemeral vulcanian products provides a unique window to better characterize the hidden state and processes that affect the upper conduit and/or the conduit-host rock interface. These processes are the source of important geophysical and geochemical signals that bear complex yet still poorly understood relationships to subsequent potentially hazardous eruptive behavior.

[22] **Acknowledgments.** This work was supported by the Government of Montserrat, the Seismic Research Center and the Institut de Physique du Globe de Paris. We thank MVO staff and volunteers for their assistance. G. Scott (Caribbean Helicopters) and the Lynx flight crew (HMS Waveruler) provided skillful access to the sampling sites. We thank J-B de Chabalier (OVSG-IPGP) for airborne photographs (TropicAir). B. Tonge (Montserrat Utilities) provided rainfall data. Guadeloupe radiosonde wind data were obtained from the University of Wyoming at http://weather.uwyo.edu/upperair/sounding.html. We are grateful to DLR (Germany) for TerraSar-X satellite imagery. We thank two anonymous reviewers for critical comments which improved the manuscript. IPGP contribution 2625.

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